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Ministry of Power

Chief Scientist's Division

Gasification of Pulverised Coal at High Intensity in a Bed of Lump Fuel under Pressure

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Based on various investigations carried out by the VTI, a new type of high-intensity gas producer has been developed for use with gas turbine plants, operating under pressure with continuous liquid slag removal (1). The gas producer developed possesses a number of important technical and structural advantages; however, since in this gas producer as well as in conventional producers lump fuel is used, the application of such producers, especially in stationary plant is somewhat limited.

The use of low-grade, and above all, of pulverized fuel would permit the field of application of gas turbine plants using high-intensity gas producers to be considerably enlarged and full benefit to be derived from their advantages. Good prospects are held out by the method evolved by the Laboratory of Combustion Physics, which involves combined combustion and gasification of p.f. in a bed of lump fuel, based on the furnace process.

When injecting p.f. with blast directly into the bed of burning lump fuel, the paths of the moving particles and conditions of combustion differ sharply from those prevailing in flame and even cyclone combustion. Due to the strong turbulence in the gas stream and the powerful radiation from the burning fuel, the p.f. entering the bed, burns and is gasified with exceptionally high intensity on the surface of the lumps and in the voids of the bed. The high temperatures in the combustion zone, which in the furnace process attain 1,700-1,800°C., also contibute towards this, as does the highly reactive surface developed by the p.f. particles, which are deposited on the slagging surface of the fuel lumps and which fill the voids in the bed. The high intensity of the combustion is also enhanced by the considerable relative velocity of gas flow around the surface of the p.f. particles, which provides very favourable conditions for active gas exchange on and near the reactive surface. Under these conditions the consumption of lump fuel can be insignificant, since the p.f. entering with the blast is deposited on the surface of the lumps, is rapidly heated, ignites and burns, thus largely preventing combustion of the fuel forming the bed.

The first experimental investigation of the combustion of p.f. in a bed of lump fuel by the furnace method (2), showed the efficiency of this method; a more detailed examination of this process, however, could only be carried out after completing investigations of high-intensity gasification of lump fuel and developing a more acceptable design of the gas producer (1).

Experimental Procedure

In order to carry out experiments with p.f., the existing experimental equipment was used; this had an output of up to 350 kg/h, and had been previously used for investigating the gasification of lump coal under pressure (1). The equipment was supplemented only by a p.f. feeder of the star-wheel type with reducing gearing and an electric motor, as well as lin[illegible] for injecting p.f. particles through the blast tuyeres of the gas produ[illegible]. The p.f. was loaded into one of the two bunkers existing in the plant; th[illegible] was charged with lump fuel.

Fig. 1 shows the experimental plant. From hopper 1 the lump fuel passes through the fuel valve 2 and the funnel 3 into the hearth of the gas producer 4. From hopper 5, the p.f. by means of the feeder 6, controlled by reducing gearing 7, is fed into the receiver 8, where it is entrained by the air, and is injected through the air tuyeres 9 into the burning bed of lump fuel in the furnace.

N.B. See page 8 for list of symbols employed in this paper.

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As a result of the great intensity of combustion, high temperatures develop in the furnace, and the fuel ash becomes liquid. This molten slag flows continuously through the slot-shaped slag outlet 10, formed by horizontally placed gates 11, into the slag receiver 12, where it is granulated in the water bath and is then removed in a solid form.

As they flow through the fuel bed, the products of gasification formed in the furnace, become enriched with CO as a result of decomposition of CO_2 at the surface of the fuel and in the fuel bed voids, that are filled with suspended p.f.; subsequently the gases enter the gas offtake 13. A small part of the gas is led off from the furnace together with the slag through the tap into the slag receiver, and from there through the gas offtake 14 into the gas manifold, where it is mixed with the principal gas stream. Subsequently the gas enters the cyclone 15, and after removal of the entrained matter, is led through the throttle valve 16 into the stack 17. In the stack a special gas sampling probe 18 is placed, which serves to determine the dust-content of the gas. Fig.1 shows the arrangement of gas sampling points and of the control and instrumentation, by means of which the basic characteristics of the process are determined.

All experiments were carried out with a cold air blast at an almost constant air rate; this amounted to an average of 1,330 kg/h, and corresponded to a fuel loading of 1,750 $kg/m^2/h$ or 12.5×10^6 $kcal/m^3/h$. The p.f. feed rate in the experiments varied from 0-255 kg/h; the consumption of lump fuel was 115-105 kg/h.

Altogether 26 experiments have been carried out, including preliminary tests. Experiments were carried out with pulverized lean coal and anthracite of different particle size grading (R_{88} from 10.8-67.8%) and with various ash-contents A^a (from 13.4 - 24.5%). Analyses of the fuels employed in the experiments are shown in Tab. 1.

During the experiments the following data were recorded: air consumption, pressure in the gas producer, composition and temperature of the gas in different sections, consumption of lump fuel and p.f. during the experiments (difference by weight before and after completion of the experiment), amount of dust collected by the cyclone, dust-content of the gas downstream of the cyclone, size distribution and ash-content of the p.f. feed and of the entrained dust collected the cyclone, as well as the ash-content of the dust, sampled by the gas sampling probe downstream of the cyclone.

Table 1. Analysis of lump anthracite and of the gasified p.f.

Date of delivery	Analysis of lump anthracite									
	W^a	A^a	$S^d_K + S^d_{op}$	C^d	H^d	N^d	O^d	V^d	Q	Size of lumps mm.
3.9.56	2.0	12.5	2.3	94.7	1.7	0.8	0.5	4.2	6850	10-50

Group No.	Date of Delivery	Characteristics of gasified p.f.										No. of experiment
		W^a	A^a	V^a	Characteristics of coke ↔	Residue on sieve % 833	417	208	124	88	74	Bottom
					Anthracite							
I	1.7.56		15.0		Powder			3.6		10.8		99.6	8-15
VIII (recycled)	1 Qtr.56.		14.8		The same	13.20	30.20	47.80	60.00	67.40	73.00	99.20	24
IX	17.4.57		24.5		do.	0	0.08	0.48	5.28	13.08	21.08	99.48	25-26
					Lean Coal							
II	21.8.56	0.5	15.0	11.9	Powder	0.20	1.48	2.88	9.88	15.48	99.48	-	16
III	9.1.57	0.5	15.0	-	do.	0.04	-	-	4.84	-	99.24	-	17-20
IV	28.2.57	1.3	13.7	-	do.	4.80	12.40	24.00	42.00	54.60	62.80	99.60	21-22
V	13.3.57	1.3	13.4	14.9	do.	4.80	13.80	31.00	50.60	63.00	69.00	99.20	22
VI	18.3.57	1.4	13.9	14.8	do.	12.20	25.40	43.00	58.20	67.80	72.60	99.20	23-24
VII	28.3.57	1.6	14.8	14.9	do.	2.80	9.08	20.88	37.68	50.68	57.88	99.28	24

= R_{88} = residue on sieve size 88 (the system of screen sizes used is not stated.)

↔ i.e., assay coke type.

/ probably means cumulative total.

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Owing to the lack of reserve hoppers for the fuel, the duration of experiments did not exceed 4 h. In the first experiments difficulties were experienced with the p.f. due to fuel blockages in different sections of the p.f. line. Subsequently, however, these difficulties were eliminated by correctly distributing the pressure along the line and by blowing upwards into the cells of the feeder during the discharge of p.f. As shown by observations, despite the fact that the p.f. and the air were fed into the furnace entirely cold, the combustion process with liquid slag removal proceeded completely normally, similar to experiments without p.f. injection.

Experimental Results

The results obtained in experiments permitted the principal characteristics of this new and highly promising process of burning p.f. in a bed of lump fuel to be determined, a process which to date has not been investigated in practice. These characteristics include: the efficiency of combustion of the p.f. and the ratio of the consumption of lump to pulverized fuel at a given loading, the composition of the gas produced, the dust-content of the gas downstream of the gas producer and after cleaning by the cyclone, the unburned carbon and the size distribution of the entrained matter, the discharge of liquid slag, etc.

In order to show more clearly the relationship between the characteristics mentioned and the basic parameter B_n (p.f. feed rate), experiments were carried out with a constant air consumption of G_b = 1330 kg/h and at a pressure of p = 5 atm. Only four experiments were carried out at a pressure of 3.5 and 7 atm. which, of course, were not sufficient to draw reliable conclusions regarding the effect of pressure on the combustion of p.f. in the bed.

Nevertheless, examination of experimental data obtained at different pressures has shown that if the p.f. feed rate is related to the operating pressure in the experiment, the scatter of the plotted experimental data is considerably smaller than is the case if the pressure is not taken into account. Consequently, in a number of instances the process characteristics were plotted as a function of the value $\frac{B_n}{p}$ i.e. of the p.f. consumption per atm. pressure.

Fig. 2 shows the dust-content of the gas as a function of the p.f. feed rate divided by the pressure in the gas producer $\frac{B_n}{p}$. As shown in the diagram, at values of $\frac{B_n}{p}$ up to 20 (which corresponds, at p $\geq$ 5 atm. to a p.f. consumption of approximately 100 kg/h), the dust-content of the producer gas ψ_{zz} hardly varies, being approximately 15 g/Nm^3. In further increasing the p.f. feed, however, ψ_{zz} increases proportionally indicating that unburnt carbon is carried out of the gas producer.

An entirely different kind of relationship is observed with regard to the dust-content of the gas after cleaning by the cyclone. As shown in the diagram, ψ_{zu} is not dependent upon the p.f. consumption and in all regimes amounts to only about 3 g/Nm^3. This means, that with increased p.f. feed rate, the increase in entrained matter is due to larger sized particles; the finer particles evidently are completely burnt in all instances.

The characteristic curve of gas dust-content shown in Fig.2 relates to the dust from two different types of coal and to two samples of p.f. fed, which differ considerably in their size distribution. A simultaneous interpretation of both sets of data obtained was found to be possible on account of the negligible difference in the ash-content and in the ultimate analysis of the fuels employed (anthracite and lean coal); also because the particle size characteristics of the entrained matter are independent of the particle size of the p.f. feed, as was established in the experiments.

This is easily seen, if we compare the particle size characteristics of the entrained matter, intercepted by the cyclone (Table 2), with the size distribution of the p.f. feed as shown in Table 1. Analysis of these data shows that the values of the particle size distribution of the entrained matter are of the same order even when employing p.f. having different degrees of fineness of grinding.

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Table 2. Particle size distribution of the dust intercepted by the cyclone

No. of experiment	Regime	Residue on the sieve %						
		833	417	208	124	88	74	Bottom*
11	I	9.4	22.6	37.92	47.72	56.0	62.52	99.32
12	I	6.2	17.5	30.3	39.9	48.50	54.40	99.80
13	I	13.4	28.20	44.60	54.20	61.60	67.88	98.28
14	I	7.6	22.84	42.88	54.96	63.26	69.16	98.76
18	I	5.82	15.45	24.74	31.74	38.54	43.78	99.25
19	I	15.40	32.60	46.80	56.80	64.40	68.20	99.20
20	I	11.40	27.40	48.20	64.60	72.80	77.40	99.40
21	I	2.5	9.04	20.54	38.24	52.34	60.04	99.24
22	I	1.80	4.60	11.30	28.20	45.40	54.30	99.70
23	I	1.40	6.20	17.10	38.90	55.60	63.40	99.20
	I	0.40	2.60	10.20	28.20	44.80	55.0	98.60
24	II	5.20	23.60	44.00	59.60	68.40	73.80	99.20
	I	0.20	0.88	2.16	6.16	16.36	25.56	99.96
25	II	5.60	14.80	24.40	33.60	44.20	52.00	99.00
	III	1.00	3.80	8.40	17.00	33.00	45.00	99.40
26	I	13.0	30.40	52.00	67.60	75.20	78.80	97.40
	II	14.00	34.80	55.00	68.60	76.20	80.20	98.20

When gasifying quite fine p.f., R_{88} = 10.8% - 15.4%, and when gasifying extremely coarse p.f., R_{88} = 54.6 - 67.8%, the R_{88} value for the entrained matter intercepted by the cyclone varies within similar limits, amounting in the first instance to 48.5 - 76.2% and in the second to 44.8 - 68.4%.

It is interesting to note that in gasifying finer p.f. the R_{88} value for entrained matter considerably exceeds the R_{88} value of the p.f. feed; this is observed both with anthracite and with Ekan coal. When employing coarser p.f. feed, the R_{88} value of entrained matter was found to be comparable with the R_{88} value of the p.f. feed.

Fig. 3 shows the ash-content of the entrained matter intercepted by the cyclone, as a function of the p.f. feed rate. As shown in the diagram, the ash-content of the entrained matter decreases considerably with increased p.f. feed rate. This proves that with an increased p.f. feed rate, the unburnt carbon carry over increases.

Fig. 4 shows the content of unburnt carbon in the entrained matter from the gas producer and downstream of the cyclone as a function of the value $\frac{B_n}{B}$, where

$$q_y^{12} = \frac{V_g \left[\varphi_4 (1 - A_4) + \varphi_{34} (1 - A_{34}) \right]}{1000 \left[B_k (1 - A_k^p - W_k^p) + B_n (1 - A_n^p - W_n^p) \right]} 100\% \qquad (1)$$

and

$$q_y^{34} = \frac{V_g \varphi_{34} (1 - A_{34})}{1000 \left[B_k (1 - A_k^p - W_k^p) + B_n (1 - A_n^p - W_n^p) \right]} 100\% \qquad (2)$$

V_g - gas output, Nm^3/h;

B_k and B_n - feed rate of lump and pulverized fuel, kg/h;

φ_{34} - amount of dust collected by the cyclone per 1 Nm^3 of gas, g/Nm^3;

A_k^p, W_k^p, A_n^p, W_n^p - ash and moisture-content of lump and pulverized fuel.

According to the diagram q_y^{12} increases proportionally if $\frac{B_n}{B}$ increases above 15. The content of unburnt carbon in the gas leaving the cyclone, however, remained unchanged in all experiments; q_y^{34} was independent of p.f. feed rate

* See previous footnote.

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and represented about 1% of the combustible matter of the fuel. This fact proved to be of considerable importance, since the dust intercepted by the cyclone, can be recycled to the gas producer and burnt.

Thus, even with a high p.f. feed rate - more than 2.5 times the consumption of lump fuel - losses incurred by incomplete combustion, ultimately represented only 1%.

Fig. 5 shows the percentage of gasified p.f. as a function of the value $\frac{B_n}{p}$.

The proportion of gasified p.f. to the total amount of p.f., fed to the gas producer, was calculated from the equation

$$b_{n,gas} = \left[1 - \frac{(q_y^{22} - q_o^{22})\left[B_k (1 - A_k^p - W_k^p) + B_n (1 - A_n^p - W_n^p)\right]}{100 (1 - A_n^p) B_n}\right] \times 100\% \qquad (3)$$

where q_o^{22} is the carry over of unburnt carbon from the gas producer operating only on lump fuel ($q_o^{22} = 3.8\%$).

As is evident from Fig.5, up to a B_n value of the order of 15-16, 100% of the p.f. fed is gasified. At $\frac{B_n}{p} = 20$ the ^{p}unburnt carbon is approximately 5%. With a further increase of $\frac{B_n}{p}$, the amount of unburnt carbon increases considerably and at a maximum ^{p} p.f. feed rate it constitutes almost half of the total amount of p.f. admitted with the blast.

Fig. 6 shows the consumption of lump fuel as a function of the p.f. feed rate. The value B_k, which is also included in the equations (1), (2) and (3), is determined from the equation

$$B_k = \frac{G_k - B_k^o \tau_{on}}{\tau_{on}} \quad [kg/h], \qquad (4)$$

where G_k is the consumption of lump fuel in the experiment;

B_k^o - the mean hourly consumption of lump fuel without injecting p.f. into the gas producer ($B_k^o = 315$ kg/h);

τ_{on} and τ_{on} the time of operation of the gas producer with and without p.f. injection.

According to Fig. 6 the increase in p.f. feed rate to 100-120 kg/h results in a sharp drop in the consumption of lump fuel; however, if B_n is further increased, the value B_k alters less sharply due to the ever increasing carry over of unburnt carbon.

In analysing the combustion conditions of p.f. in a bed of lump fuel, we must take into consideration that in the experiments the air consumption was practically constant; therefore, the ratio of the air consumption to the p.f. charged simultaneously, varied considerably from experiment to experiment. At low p.f. feed rate consumption it attained quite high values, whereas with increased p.f. feed rate consumption it decreased noticeably.

The ratio referred to above can be expressed in terms of excess air α, as generally accepted in fuel technology, referred, however, in this particular instance, not to the total amount of fuel consumed in the gas producer, but only to the p.f. i.e. the excess air in the p.f. suspension, entering the gas producer through the tuyeres α_n. These values are given along the abscissa in Figs. 4 and 5 together with the values of $\frac{B_n}{p}$, for p.f. feed rate. As shown in the curve of Fig. 5, at α_n values of 1 - 1.5, i.e. when there is a considerable amount of excess air, combustion of the p.f. is sufficiently complete. With increasing amounts of p.f. charged, α_n decreases correspondingly, attaining finally a value of the order of 0.6; this shows that there is insufficient air for effective combustion in the vicinity of the tuyeres, and it is for this

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reason that a considerable decrease in the quantity of p.f. gasified is observed.

It is evident that in the range of values $\eta_n < 1$, the carbon content of the p.f. can only be burnt in the presence of a vigorous gasification reaction with a fully developed reduction zone, i.e. with a deeper bed level than exists in the present experiments, and with a more favourable heat regime in the process. This latter can be achieved easily by preheating the air and partly preheating the p.f.

Despite the considerable entrainment of unburnt p.f. from the bed at high feed rates, the p.f. is intensively gasified, and even with a comparatively shallow bed (of the order of 0.5 m) produces a gas having a similar composition as regards its combustible components to that produced by the gasification of lump coal.

The percentage of combustible components in the main gas stream (on leaving the shaft) was: CO - 22-23%, H_2 - 3-4%, CH_4 -0.4-0.8%. The CO_2 content constituted approximately 7%. The calorific value of this gas was approximately 850 kcal/Nm^3.

Since the composition of the gas passing through the slag tap is characterised by an increased CO_2 content (up to 15%), the combined gas in the manifold after mixing the two gas streams had a calorific value of the order of 750 - 800 kcal/Nm^3, i.e. approximately 150 kcal lower than when gasifying lump fuel.

It should be noted, that in making direct use of this gas in gas turbine plants its decreased calorific value cannot affect the efficiency of the plant, or the combustion conditions, since it has a temperature above 1,000°C., i.e. considerably higher than the ignition temperature.

Fig. 7 shows the mean CO_2 content of the gas on leaving the shaft and after mixing in the manifold at different p.f. feed rates during the experiment. As shown in the diagram, variation over a wide range of the rate of p.f. feed has practically no effect on the gas composition. A noticeable decrease in the CO_2 content (2-3%) in experiments without p.f. feed, i.e. at $B_n = 0$, is not accidental, since a similar gas composition has previously been observed in a number of experiments with lump anthracite without p.f. injection into the bed (1).

Analysis of the data relating to the discharge of ash as slag, shows that with increased p.f. consumption, the amount of liquid slag, run off the gas producer, is slightly decreased (Fig.8). The value for slag discharge a_{sl} is related to the ash carried over from the producer and the ash content of the initial fuel by the expression:

$$a_{sl} = \left[1 - \frac{V_2 \left(\varphi_{zu} A_{zu} + \varphi_n A_n \right)}{1000 \left(B_z A_z^p + B_n A_n^p \right)} \right] 100\% \qquad (5)$$

In some cases the slag discharge was checked by direct weighing. A comparison of the results showed good agreement.

Conclusion

The results of the experiments carried out show the possibility of intensively gasifying p.f. including even such unreactive fuels as anthracite in a bed of lump fuel under pressure, at loadings of 1700-1800 kg/m^2/h and at heat rates referred to the working volume of the gas producer above 12.10^6 kcal/m^3/h.

Despite the fact that the experiments were carried out in a gas producer which was not specially designed for the process, and without preheating the air and p.f. it was possible for the first time to gasify pulverized lean coal and anthracite in amounts exceeding 50% of the lump fuel consumed while obtaining gas of similar purity and similarly steady slag removal as when gasifying coal without p.f. injection.

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The maximum consumption of p.f. obtained in the experiments was of the order of 250 kg/h, which exceeded the consumption of lump fuel 2.5 times. Despite the fact, however, that at this rate increased entrainment of dust from the gas producer occurred, nevertheless the fact that the entrained solids were of a coarse particle size and therefore easily intercepted by the cyclone, enabled a gas of an adequate degree of purity to be obtained after this had been subjected to similar cleaning processes as are employed in the gasification of lump fuel.

The possibility of recycling the intercepted entrained solids with the blast, ensures a high efficiency for the combined process and permits the total losses due to unburnt carbon to be reduced, to a q_4 value of approximately up to 1%.

The experiments did not establish that the size grading of the p.f. (R_{88} = 10.8 - 67.8%) had any noticeable effect on the characteristics of the process, which indicates that it is possible to use p.f. that is quite coarsely ground or crushed.

The experiments have established that the p.f. can be intensively gasified in a shallow bed of lump fuel (of the order of 0.5 m.) with only a slight decrease in the calorific value of the gas as compared to the gas obtained without p.f. injection (e.g. 800 kcal/Nm^3 as compared to 900-950 kcal/Nm^3). Varying the pressure from 3.5-7 atm. has practically no effect on the gas composition, and only slightly improves the combustion of the p.f. in the gas producer. With p.f. injection, the discharge of liquid slag from the bed on average is similar to that when gasifying lump fuel, but slightly decreases with increased p.f. feed rate however only within the range of 90-75% of the ash-content in the starting fuel.

The results of the investigation show that the new method of combined gasification of pulverized and lump fuel is highly efficient.

An analysis of the design of the gas producer, operating according to this method, shows that a sufficient depth of the bed in the shaft should be maintained in order to improve gas filtration and ensure the maximum development of the reduction zone, as well as an adequate distance between the tuyeres and the slag tap, which is required to effect satisfactory combustion of the p.f. in the lower part of the furnace. It might also be found useful, to employ pulsating or alternating injection through the tuyeres, which improves the combustion conditions of the p.f. and prevents slagging of the tuyeres.

The results of the present investigations can find immediate practical application for the employment of solid fuel not only in gas turbine plants but also for firing steam boilers after suitable modifications have been made.

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A_n^p	ash content of p.f.
W_n^p	water content of p.f.
q_y^{zz}	unburnt carbon downstream of gas producer
q_y^z	unburnt carbon downstream of cyclone
q_o	unburnt carbon carryover downstream of gas producer operating on lump fuel only
G_k	consumption of lump fuel in experiment
B_k^o	mean hourly consumption of lump fuel without p.f. injection
τ_{nn}	time of operation of gas producer with p.f. injection
$\tilde{\iota}_{\sigma n}$	time of operation of gas producer without p.f. injection
α_n	excess air referred only to p.f.
a	slag discharge
A_z	ash downstream of cyclone
A	ash intercepted by cyclone
q_4	probably total losses due to unburnt carbon
R_{88}	residue on sieve 88
A^c	Ash content
W^a	Water content
V^2	volatile matter
$S_k^2 + S_{op}^2$	Sulphur content
C^2	carbon
H^2	hydrogen
N^2	nitrogen
O^2	oxygen
Q_n^a	c.v.
B_n	p.f. feed rate
B_k	lump fuel feed rate
G_b	air rate
p	pressure in atm.
φ_{zz}	dust content of producer gas upstream of cyclone.
φ_z	dust content of producer gas downstream of cyclone
V_z	gas output
φ	quantity of dust intercepted by cyclone.
A_k^p	ash content of lump fuel
W_k^p	water content of lump fuel

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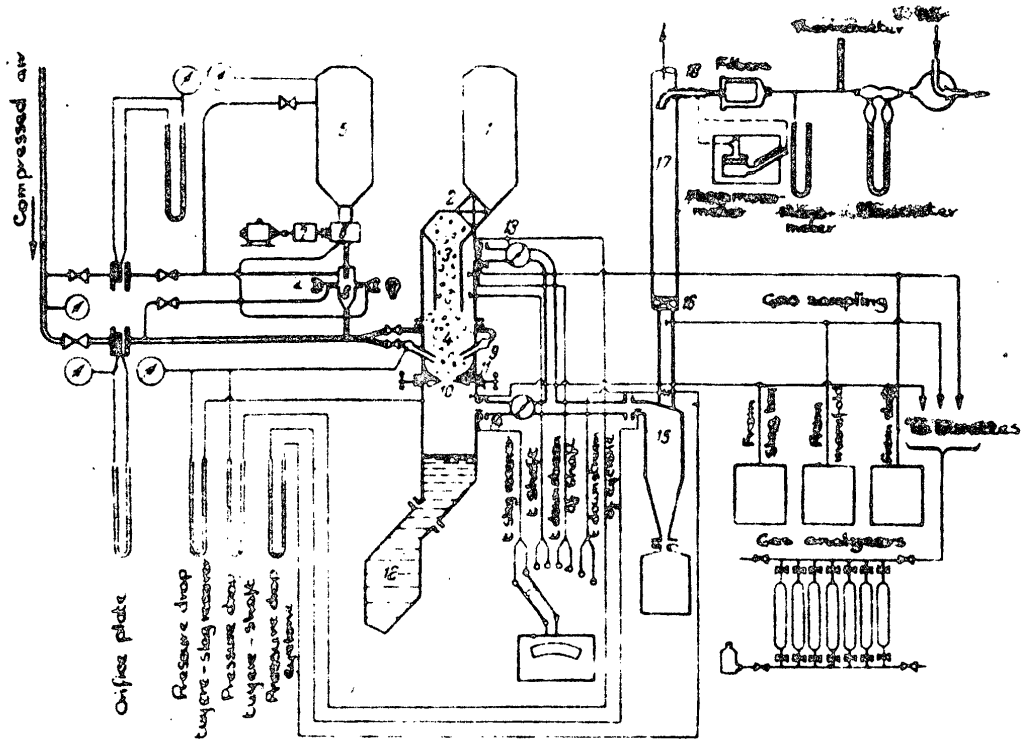

Fig.1. Diagram of experimental plant and arrangement of instruments and equipment.

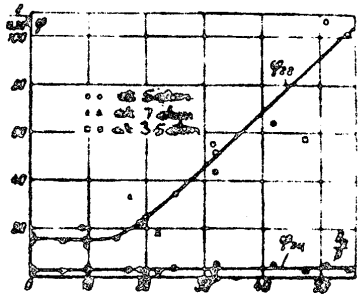

Fig.2. Dust-content of the gas downstream of the gas producer φ_{zz} and downstream of the cyclone φ_{zu}, as a function of the value $\frac{Bn}{p}$

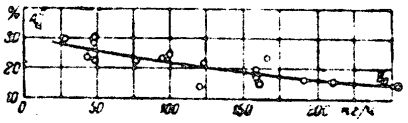

Fig.3. Ash content of the entrained solids intercepted by the cyclone A_{up} as a function of the p.f. consumption B_n

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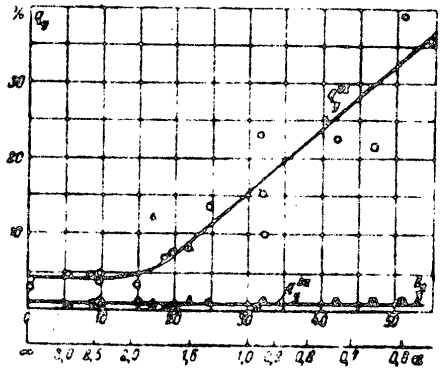

Fig.4. The content of unburnt carbon in the entrained solids downstream of the gas producer q_y^{zz} and downstream of the cyclone q_y^{zk} as a function of the values $\frac{B_n}{p}$ and α_n

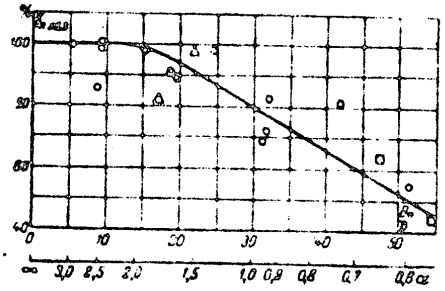

Fig.5. Percentage of the gasified p.f. $B_{n.raz}$ as as function of the values $\frac{B_n}{p}$ and α_n

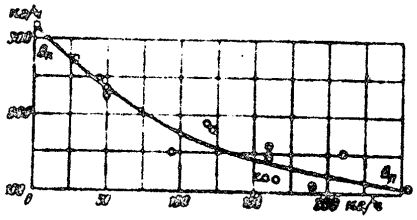

Fig.6. Consumption of lump fuel B_k as a function of p.f. consumption B_n

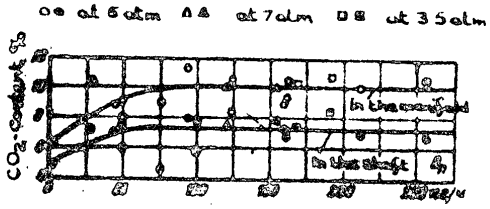

Fig.7 CO_2 content in the gas at different p.f. feed rates

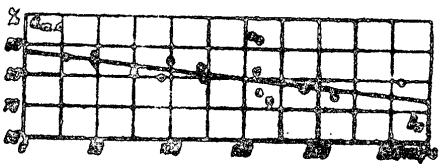

Fig.8. Discharge of ash in the slag a ω as a function of p.f. feed rate B_n

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